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Coastal and river flood risk analyses for guiding economically optimal flood adaptation policies: a country-scale study for Mexico

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Many countries around the world face increasing impacts from flooding due to socio-economic development in flood-prone areas, which may be enhanced in intensity and frequency as a result of climate change. With increasing flood risk, it is becoming more important to be able to assess the costs and benefits of adaptation strategies. To guide the design of such strategies, policy makers need tools to prioritize where adaptation is needed and how much adaptation funds are required. In this country-scale study, we show how flood risk analyses can be used in cost–benefit analyses to prioritize investments in flood adaptation strategies in Mexico under future climate scenarios. Moreover, given the often limited availability of detailed local data for such analyses, we show how state-of-the-art global data and flood risk assessment models can be applied for a detailed

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assessment of optimal flood-protection strategies. Our results show that especially states along the Gulf of Mexico have considerable economic benefits from investments in adaptation that limit risks from both river and coastal floods, and that increased flood-protection standards are economically beneficial for many Mexican states. We discuss the sensitivity of our results to modelling uncertainties, the transferability of our modelling approach and policy implications.

This article is part of the theme issue 'Advances in risk assessment for climate change adaptation policy'.

1. Introduction

Economic impacts from natural disasters have been increasing during the last decades in many areas around the world [1]. Most studies examining the trend in historical natural disaster losses have concluded that increases in risks have been mainly caused by population and economic growth [2], while part of the trend may also be caused by natural and man-made climate change [3]. In the future it is expected that climate change may increase the intensity and frequency of certain extreme weather events [4]. This implies that future natural disaster risk could increase further.

Climate change adaptation strategies can limit the expected increase in natural disaster risks. Examples are installing new, or strengthening of existing, flood-protection infrastructure to protect against sea-level rise and peak river discharges. For the design of such strategies it is imperative to have a good understanding of potential hazard characteristics and natural disaster risk under current as well as future climate conditions. For instance, insights into the areas that can potentially be inundated, flood water depths and flood damage can help identify flood-prone areas where flood-protection infrastructure is needed. Given the long lifespan of several flood-protection measures, like dykes, estimates of potential future flood hazard characteristics and risks are useful for designing flood-protection strategies that can cope with the impacts from climate change and the increasing risk due to socio-economic growth [5]. Moreover, such estimates of natural disaster risk can be used as input for cost–benefit analysis of climate change adaptation strategies by providing information on the benefits, or avoided damage, of these strategies [6,7]. Cost–benefit analysis can provide insights into the economic return on investments in climate change adaptation, and thereby help in prioritizing economically desirable investments [8].

Owing to the low-probability nature of natural disaster risk, there is often a lack of empirical observations of natural disaster losses for a specific area. For this reason, natural disaster risk assessments are often based on 'catastrophe models' instead of historical loss records [9]. For assessing flood risk, such models are called flood damage models, which usually consist of the following steps (see e.g. [10] for a review). First, flood hazard characteristics are estimated using hydraulic modelling driven by hydrological models or observed discharge. This hazard analysis results in flood inundation maps that show, for example, inundation depths in each location with various probabilities of occurrence. Second, the potential damage caused by these inundation depths can be estimated by combining the hazard characteristics with information on exposed values of properties and economic activities. This is done by applying depth–damage functions, which typify the vulnerability of exposure on the basis of the proportion of value lost for a given inundation depth. Levels of average annual flood risk can be estimated by conducting this analysis for floods with varying degrees of severity and related exceedance probabilities. Third, insights can be obtained in future levels of flood risk in a specific area by conducting this analysis for various scenarios of future climate conditions, which influence the flood hazard, and scenarios of socio-economic developments, which drive future economic values exposed to flooding.

Here we apply such a flood risk analysis method to estimate current and future levels of risk of both coastal and riverine flooding for all states of Mexico. Our analysis focuses on protection offered by dykes, which is a suitable approach for large-scale analysis [7]. However, for more local planning, other options can be considered, such as floodplain zoning, beach nourishment or realignment, creating room for the river and integrated flood risk management. While similar approaches like this study have been applied for regions where high-resolution data are available [6,11], and others have investigated local flood hazard characteristics for Mexico [12–15], we demonstrate here how global datasets can be applied in combination with a cost–benefit analysis in data-scarce countries like Mexico to guide policy makers. To our knowledge, besides our previous study for the Mexican state of Tabasco [16], the only other study that applies a similar approach with global datasets is by Ward *et al*. [7], but that study is limited to river flood risk and urban areas. In this study, we analyse total risk (i.e. not limited to urban) for river and coastal floods, and we explicitly show the effects of adaptation on risk, and the costs involved in achieving economically optimal protection standards for different parameter settings. Moreover, Ward *et al*. [7] provide a global assessment, while we demonstrate how our methodology can be applied to inform (sub-)national decision-making. Our analysis is done for the current climate as well as scenarios of climate change, which provides insights for current flood risk management practices and flood risk adaptation plans that are being designed by the Mexican government.

2. Case study: Mexico

Mexico experiences destructive river or coastal floods almost on a yearly basis, which cause substantial economic damage. Mean annual rainfall for Mexico is 780 mm, which leads to 410 billion m^3 in runoff per year [17]. Climate zones vary greatly, ranging from tropical rainforest in the south, mountainous regions in the centre and arid deserts in the north of Mexico, leading to large variations in runoff. As people settled in areas with water availability, now 75% of the total runoff occurs in areas where large cities and population, industry and agriculture are located [17]. Moreover, due to its geographical location, meteorological conditions and topographical characteristics, many parts in Mexico are subject to frequent flash floods or lengthy river flooding. For instance, in winter, cold fronts lead to heavy rainfall in the northeastern states along the Gulf of Mexico and the Yucatan peninsula, or intense rainfall from convective storms over central Mexico [18] and hurricanes frequently cause heavy rainfall leading to flood events [18–20]. It is estimated that 90% of damage caused by natural hazards in Mexico is related to hydro-meteorological events such as flood or droughts [17]. On average, 500 floods occur each year in Mexico, mostly in the southern, central and northeastern parts throughout the rainy season, but also in the more arid northwestern part of the country [18].

Both the eastern and western parts of the country are subject to hurricane landfall, as the Gulf of Mexico and the northeastern Pacific are among the most active regions for hurricanes in the world. Besides rainfall, these hurricanes also cause storm surge setup, leading to coastal inundation. Since 1998, at least four major coastal floods have been reported in Mexico, resulting in the death of 912 individuals and billions of US dollars' (USD) worth of economic damage [21]. For instance, a major coastal flood during hurricane Emily in 2005 caused economic damage of several hundred million USD [19]. More recently, in 2013 Mexico was hit by two storms simultaneously: tropical storm Manuel in the Pacific and hurricane Ingrid along the Caribbean coast. Together they affected 77% of Mexico's land extent, resulting in severe flooding [20]. Owing to the diversity of existing climate systems in Mexico, climate change is expected to exacerbate river flood hazards in some states where it is expected to become wetter, but reduce it in others due to drying, although this is uncertain and depends on particular climate change scenarios. Moreover, sea-level rise probably leads to exacerbated risk in coastal lowlands, especially on the Yucatan peninsula or the northwestern states of Sonora and Baja California [17]. Therefore, it is relevant to conduct a flood risk analysis for each state under a variety of possible future climates.

3. Methods

(a) Modelling river and coastal flood risk

(i) Flood risk assessment

Flood risk is often expressed in terms of expected annual damage (EAD), which is a monetary value (USD year^{-1}). The EAD is calculated as a function of: the hazard (§3a(ii)), modelled as inundation maps for various return periods; the exposure (§3a(iii)), modelled as land-use maps and corresponding land-use values; and the vulnerability (§3a(iv)), which describes the relation between the inundation depth and how much damage is caused. The EAD is then obtained by computing the damage that would occur in each cell for each return period. These values are then aggregated to state level, and these are then plotted on an exceedance probability–loss curve. Risk is estimated by applying a trapezoidal method of integration over the exceedance probability–loss curve. Moreover, when calculating the EAD, we take into account that most flood-prone regions already have some form of protection standard (§3a(v)), and that flood risk is subdivided into direct damage (property losses) and indirect damage, such as business interruptions (§3b). Electronic supplementary material, figure A1, shows this modelling framework, which is described in detail in subsequent sections. In this study, we apply this modelling framework to assess current and future flood risk, and to calculate the costs and benefits of increasing flood-protection standards (§3b). Supporting data tables for the results are provided in electronic supplementary material B and tables for the sensitivity analysis are provided in electronic supplementary material C.

(ii) Hazard

River

For developing the hazard maps for river floods we use the GLObal Flood Risk with IMAGE Scenarios (GLOFRIS) modelling cascade [22,23]. The GLOFRIS modelling cascade simulates daily gridded discharge and flood volumes, and is forced with EU watch data to represent current climate conditions [24]. For the future climate scenarios, the GLOFRIS model cascade is forced with five global climate models [25] for the period 2060–2099 to represent conditions in 2080: HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M. Flood volumes are obtained by fitting a Gumbel distribution for the annual hydrological year time series for maximum flood volumes for different return periods: 5, 10, 25, 50, 100, 250, 500 and 1000 years. These flood volumes are then converted into inundation maps ($30'' \times 30''$ resolution) using the inundation downscaling model of GLOFRIS [23]. Note that these hazard maps (and those for coastal hazards) represent return periods per cell, and do not represent real events or the interdependence of upstream–downstream effects. The hydrological–hydraulic modelling component of GLOFRIS (PCR-GLOBWB) has been validated previously on discharge [26], terrestrial water storage [27], the generated flood volumes [22] and flood extents [23]. More recently, the flood extents from GLOFRIS were benchmarked against flood extents from local modelling studies for eight locations (in the USA, Europe and Asia), showing good performance [8]. Electronic supplementary material D provides an additional analysis on observed flood extent obtained from the Dartmouth Flood Observatory (http://floodobservatory.colorado.edu/) for the Tabasco area in Mexico, providing confidence that the model performs reasonably well for Mexico. For this study, we used simulations for two representative concentration pathways (RCPs), namely RCP2.6, which represents a world with ambitious greenhouse gas reductions, and RCP8.5, which represents a world where fossil fuels are the dominant energy source.

Coast

For developing the hazard maps from coastal storm surges we use a geographic information system-based inundation model that takes into account water level attenuation and is forced by the global tide and surge reanalysis (GTSR) dataset. The GTSR is the first global reanalysis of storm surges and extreme sea levels based on hydrodynamic modelling [28]. GTSR performs similarly to many regional hydrodynamic models, and is particularly useful for estimating flood risk [28]. The inundation model uses the multi-error-removed improved-terrain digital elevation model (MERIT DEM) [29] at a 10-arcsecond resolution (approx. 350 m resolution at the equator) with an EGM96 (Earth Gravitational Model 1996) vertical datum, to which the GTSR is corrected. The MERIT DEM has 58% of global land areas mapped with a vertical accuracy of ± 2 m or better [29]. All areas that are hydraulically connected to the sea at a given extreme seawater level are inundated. Our method also takes into account a scaled water level attenuation due to surface roughness, compared to a simple planar or 'bathtub' inundation method, a method that probably overestimates risk [30–32]. In several other studies attenuation factors varying between 0.1 and 1.0 $\mathrm{m\,km^{-1}}$ were used, see for a review [31], but no (land-use-based) guidelines yet exist for applying this factor. Here, a maximum attenuation factor of 0.5 $\mathrm{m\,km^{-1}}$ is used, which is linearly scaled to account for spatial variation in roughness; it ranges from 0.0 $\mathrm{m\,km^{-1}}$ in river and lake cells with a permanent water percentage of 100% to the maximum value of 0.5 $\mathrm{m\,km^{-1}}$ in cells with no permanent water. The percentage of permanent water was derived from global surface water occurrence maps as the percentage of 30 m cells with a water occurrence larger than 50% [33]. A visual comparison of flood inundation patterns from actual flood events and modelled flood hazard maps shows reasonable agreement in flood patterns (electronic supplementary material D). We model the inundation for eight return periods: 5, 10, 25, 50, 100, 250, 500 and 1000 years. For coastal floods, we analyse the climate scenarios RCP2.6 and RCP8.5 for which sea levels are estimated to rise by 40 and 63 cm, respectively, by 2080 [15]. Moreover, as the estimates for sea-level rise (SLR) are potentially too low [34,35], we analyse the SLR100 and SLR150 scenarios, in which sea levels rise by 100 and 150 cm, respectively. A sensitivity analysis to the maximum attenuation factor and its effect on current risk is presented in electronic supplementary material, table C1. Note that in our analysis we do not account for changing intensity and frequency of hurricanes, as this is not yet well integrated in storm surge datasets [28].

(iii) Exposure

Exposure in large-scale flood risk modelling is typically modelled with land-use maps and maximum damage values for the different land-use classes. Here we use the GlobeLand30 [36] land-cover map, which is a 30 m resolution map of Earth's land cover, which we resample to the corresponding resolutions of the river ($30'' \times 30''$) and coastal ($10'' \times 10''$) hazard maps. We aggregated the land-use classes from GlobeLand30 into four sensible classes: urban, agriculture, pasture and nature. All water bodies are masked from the analysis. The maximum damage value for the urban class is derived from [37], and is constructed as the weighted average of the maximum damage values for Mexico for the residential (75%), commercial (15%) and industrial (10%) class, similar to [22]. For agriculture and pasture, the maximum damage is taken as the maximum production value per $\mathrm{m^2}$ for Mexico (http://www.fao.org/faostat/en/): 8 USD cent $\mathrm{m^{-2}}$ and 1 USD cent $\mathrm{m^{-2}}$, respectively. The maximum damage value for the nature class is difficult to estimate; we assume a small clean-up cost of 0.5 USD cent $\mathrm{m^{-2}}$, which has a minor influence on the risk estimates. A sensitivity analysis of these values is carried out in §3c. For future conditions, we assume that values increase according to the estimated growth in GDP of 3%, which is the average growth rate in the coming decades [17].

(iv) Vulnerability

Vulnerability describes the susceptibility of exposed value to damage. The common approach in flood risk modelling is to apply so-called depth–damage curves, which describe the relation between inundation depth in each cell, and the percentage of the maximum value that is damaged at this inundation depth. While other processes co-determine the damage caused to a property and land-use class, like flow velocities, this method is suitable for large-scale flood risk assessments [10]. Unfortunately, to our knowledge no depth–damage curves are available for Mexico. For agriculture we use depth–damage curves for central America [37], and also apply these for pasture and nature, as no curves are reported for these land-use classes. While [37] presents depth–damage curves for central America to construct the urban class curves, these are based on a limited amount of studies [37] that assume one-storey buildings, misrepresenting depth–damage relations for urban areas. Therefore, we apply the global average depth–damage curves from [37] instead. The uncertainty of these curves is elaborated on in §3c.

(v) Protection standards

The protection standards refer to the return period up to which structural measures provide flood protection, i.e. a 100-year protection standard prevents a flood with a return period of 100 years or lower. While protection standards can be achieved in a number of ways, the most common approach is investing in dyke structures. In this study, we derive the current protection standards from the FLOod PROtection Standards (FLOPROS) database [38] (https://www.nat-hazards-earth-syst-sci.net/16/1049/2016/), which is an evolving global database of flood-protection standards, and currently provides the only consistent dataset of flood-protection standards for Mexico (see electronic supplementary material, table B1, for all protection standards). However, due to the lack of essential datasets that resolve coastal hazards, the FLOPROS database does not hold coastal protection standards, and neither are coastal protection standards available elsewhere to our knowledge. We, therefore, assume that current coastal flood protection is the same as river flood protection. These protection standards reduce the calculated risk by truncating the EAD at the corresponding return period. Dykes are assumed not to breach below the design standards and to completely fail above design standards.

(b) Cost–benefit analysis for optimal river and coastal adaptation

The cost–benefit analysis serves as general purpose: (1) to determine whether an investment is economically sound, and (2) to determine the best choice between different flood protection standards. The first is achieved when the net present value (NPV) of an investment decision (present value of total benefits minus present value of total costs) is positive. The second is determined by analysing which of the investment decisions has the highest NPV. We apply equation (3.1) to determine the NPV of implementing different protection standards. Here $\mathrm{EADreduced}_{t,ps,i}$ is the reduction in EAD for a certain protection standard ps at time t for a particular state i; $\mathrm{Cmaintenance}_{t,ps,i}$ are the maintenance costs of the needed dykes for the protection standard ps at time t, summed for state i; and $\mathrm{Cinvestment}_{t=0,ps,i}$ are the initial investment costs, also summed for state i (see electronic supplementary material A3 for cost estimates). The NPV of a protection standard is determined over the lifespan of the dyke T, which is set at 100 years. The multiplier α describes the markup of 60% for indirect damage, and is given as $1 + \text{indirect damage factor} = 1.6$ (see electronic supplementary material A2).

$$\mathrm{NPV}_{ps,i} = \sum_{t=1}^{T} \frac{(\alpha\ \mathrm{EADreduced}_{t,ps,i})}{(1+r)^t} - \left(\sum_{t=1}^{T} \frac{(\mathrm{Cmaintenance}_{t,ps,i})}{(1+r)^t} + \mathrm{Cinvestment}_{t=0,ps,i} \right). \tag{3.1}$$

Important in any cost–benefit analysis is to determine the time value of money by applying a discount rate. For Mexico, the applied discount rate is currently 10% [39], meaning that a money stream now in 2010 is valued significantly higher than a money stream in 2080. A sensitivity analysis of this parameter is included in §3c.

(c) Model uncertainties and sensitivity analysis

This research applies a range of methods from flood risk analysis to cost–benefit analysis. Each step contains a certain degree of uncertainty. For risk estimates, these uncertainties are well described [40], and can for instance be found in the used hazard maps, land-use map, exposure values and depth–damage curves. Other uncertainties can propagate from the GLOFRIS model [22,23], the uncertainties in the GTSR dataset that was applied to model storm surge inundation depth, such as the underrepresentation of tropical cyclones or exclusion of wave run-up [28], the remaining vertical error in the DEM [29], or the assumption on coastal protection standards in the FLOPROS database [38]. Here, we provide a sensitivity analysis for key parameter estimates in this study. Especially the value of exposure and the used depth–damage curves can introduce large uncertainties [40]. As these uncertainties are related, we limit the sensitivity analysis to varying the maximum damage values between 75% and 125% of the baseline estimates (§3a(iii)). Furthermore, we vary the factor of indirect damage by analysing half the rate (30%) and double the rate (120%) for indirect damage of the baseline estimate (60%). Finally, a key parameter of the cost–benefit analysis is the discount rate that for the baseline is set at a relatively high discount rate of 10% [39]. For comparison, the European Union recommends the use of a 4% discount rate, which gives a higher weight to future values than the 10% rate (http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm). We apply a discount rate of 10%, and provide sensitivity analyses for a discount rate of 6% and 4%. We discuss the sensitivity analysis separately in §4d.

4. Results

(a) River and coastal flood risk in Mexico

(i) Current and future river flood risk

Figure 1 shows the EAD for river floods across states in Mexico for the current climate, for constant climate conditions, for the RCP2.6 and RCP8.5 climate change scenarios, and for the estimated growth in exposure as a result of economic growth, assuming no additional dyke protection. Under the current climate, average EAD per state in Mexico is estimated at approximately 200 million USD year^{-1}; Tamaulipas, Veracruz and San Luis Potosi have the highest risk, with an EAD between 400 and 800 million USD year^{-1}. The total estimated river flood risk under current climate is approximately 7 billion USD year^{-1}. The UNISDR, the United Nations Office for Disaster Risk Reduction, estimates the average annual loss for riverine flooding at 870 million USD year^{-1} for direct damage [41] (obtained from https://www.preventionweb.net/countries/mex/data/), which would lead to approximately 1.3 billion USD year^{-1} if correcting for a 60% indirect damage factor. Our higher estimates are most likely explained by the use of higher-resolution exposure data that capture more exposed urban areas, which is a major contributor to flood risk. Moreover, we find that for Tabasco reported direct and indirect damage over a 5-year period from 2007 to 2011 was approximately 1 billion USD year^{-1} [42]. While our estimate of an EAD of 400 million USD year^{-1} for Tabasco is slightly lower, the reported average is probably skewed upwards by the major flood that occurred in 2007. Still, the UNISDR estimate and the reported average damage for Tabasco are within an order of magnitude of our estimates, providing confidence in our results.

If climate remains constant, flood risk becomes highest in Tamaulipas and Veracruz, with an EAD of 29 billion and 12 billion USD, respectively. Tamaulipas, Veracruz and San Luis Potosi also face the highest risk under the RCP2.6 and the RCP8.5 scenarios, with an EAD of, respectively, 30 and 29, 12 and 13, and 51 and 69 billion USD year^{-1}. These states are home to some of the largest rivers in Mexico, such as the Rio Bravo in Tamaulipas and the Papaloapan and Coatzacoalcos in Veracruz, making them especially vulnerable to increases in inundation volumes, or increases in exposure.

While river flood risk is highest for the states along the Gulf of Mexico, the estimated relative increase caused by climate change is largest in the central states of Mexico (see electronic supplementary material, figure E1). Both the RCP2.6 and RCP8.5 scenarios show the largest relative increase in risk in the central states compared to constant climate conditions. While flood risk increases in most of the states under both scenarios, some states show a decrease in risk for both the RCP2.6 and RCP8.5 scenarios. For example, Tabasco would see a considerable decrease of risk under warmer climate conditions in the RCP8.5 scenario. When comparing the RCP2.6 and RCP8.5 scenarios, we see that the RCP8.5 leads to considerably drier conditions in the northwestern and southeastern states.

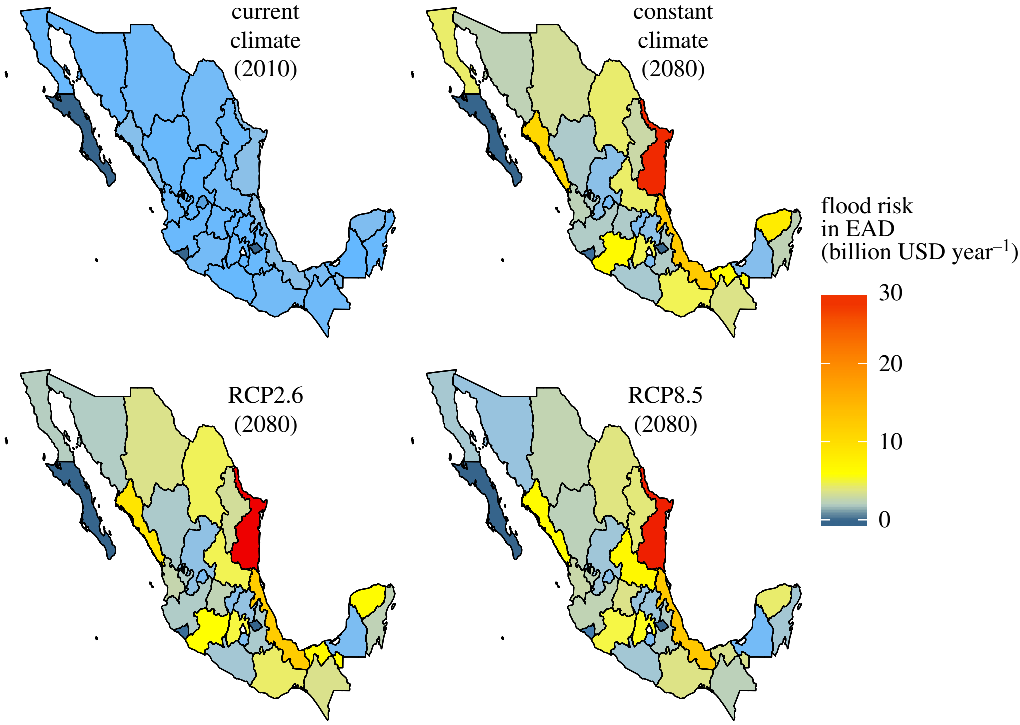

Figure 1. River flood risk expressed in EAD for the current (2010) climate and for three future (2080) climate conditions. Future risk levels are derived by assuming no additional flood protection.

(ii) Current and future coastal flood risk

Figure 2 shows the results for coastal flood risk across the Mexican states. As the climate scenarios are based on increasing sea levels, there is a consistent increase in risk from the constant climate scenario to the high SLR150 scenario. Under current climate, the estimated risk for coastal floods is considerably less than the risk for river flooding. Our results show an aggregated coastal flood risk for Mexico of little under 130 million USD year^{-1}, including both direct and indirect damage. The UNISDR reports a current average annual loss of approximately 100 million USD year^{-1} for direct damage for coastal flooding, which translates into 160 million USD year^{-1} when taking into account a 60% factor for indirect damage. These estimates are within a factor of two of the estimates in this study, providing confidence in our results.

Our results show that the current flood risk is estimated to increase to 2 billion USD year^{-1} in 2080 under constant climate conditions as a result of socio-economic growth, and approximately 10 billion under the high-end SLR150 scenario due to socio-economic growth and sea-level rise. On a state level, Yucatan is the most vulnerable to coastal flood risk, with an estimated EAD of 67 million USD year^{-1} under current climate and 4 billion USD year^{-1} under the SLR150 scenario. Together with the relatively high risk in Campeche and Quitana Roo, the Yucatan peninsula seems to be especially vulnerable to sea-level rise. Other states that are estimated to be especially vulnerable to (future) coastal flood risk are Sonora and Baja California Sur on the west coast of Mexico.

(b) Optimal protection standards and risk reduction

(i) Optimal protection standards for river floods

Figure 3 shows that under constant climate conditions, about half of the states require investments in additional protection to achieve or uphold economically optimal protection standards. For

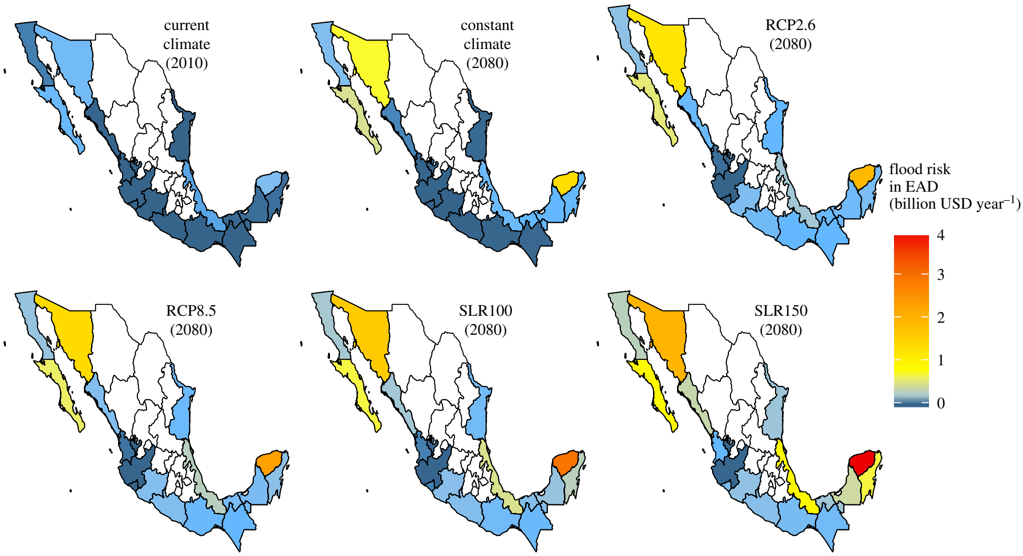

Figure 2. Coastal flood risk expressed in EAD for the current (2010) climate and for five future (2080) climate conditions. Future risk levels are derived by assuming no additional flood protection.

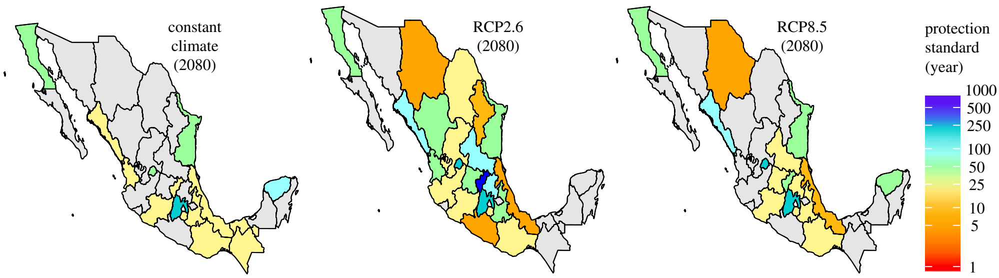

Figure 3. Optimal protection for river floods for three future (2080) climate conditions and a discount rate of 10%. The grey areas depict states where no additional investments are required as protection standards are already as high as (or higher than) the economic optimum.

instance, Chiapas, Nayarit, Puebla, Sinaloa and Veracruz need to raise the protection standard to a 25-year protection standard, Tamaulipas to a 50-year protection standard, and Yucatan to a 100-year protection standard, to reach the economic optimum. Under the RCP2.6 scenario most states are estimated to have a positive optimum NPV of additional river flood protection, mostly for the 25- or 50-year protection standards, with highest economic optimum protection standards for Mexico (250 years), Aguascalientes (250 years) and Queratero (500 years). In some states, such as Quintana Roo, climate conditions under the RCP2.6 scenario lead to less flooding compared to current climate (figure 3), causing the initial dyke height to offer higher than optimal protection standards, implying there is no need for additional investment. Vice versa, states that become more prone to flooding may need additional investments to uphold protection standards, as is for instance the case for Nuevo Leon, which needs to invest in extra dyke height to uphold a 10-year protection standard. Under the RCP8.5 scenario, optimum protection standards are mostly equal to, or lower than, under the RCP2.6 scenario.

Even though the protection standards are relatively low, the estimated risk reduction obtained by implementing additional protection achieved is considerable (see electronic supplementary material, figure E2). For instance, under constant climate, the yearly river flood risk reduced for

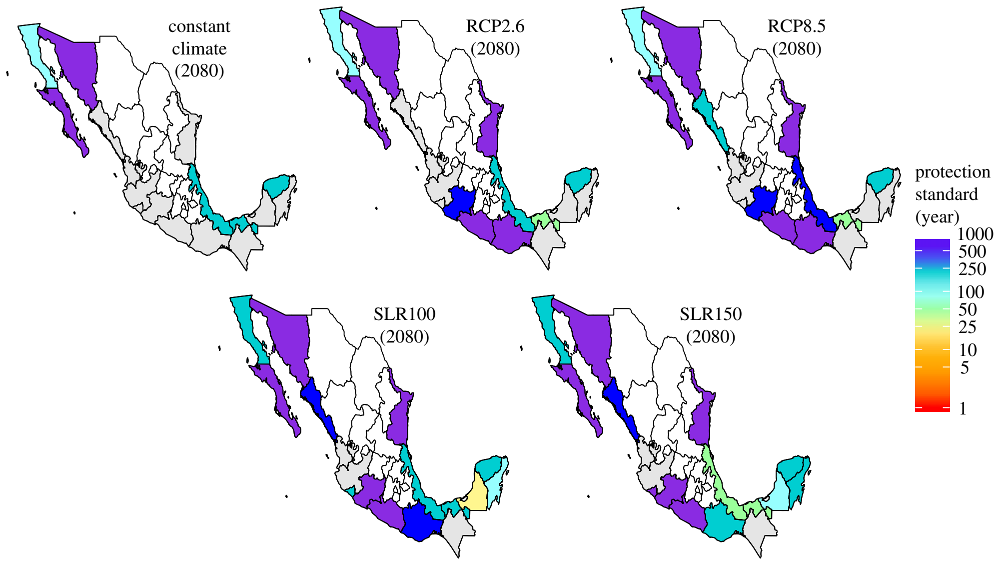

Figure 4. Optimal protection standards for coastal floods for five future (2080) climate conditions and a discount rate of 10%. The grey areas depict states where no additional investments are required as protection standards are already as high as (or higher than) the economic optimum.

states that need investments to reach economic optimum varies between approximately 50% for San Luis Potosi and 95% for Mexico when investing in optimal protection standards. For the RCP2.6 scenario, the reduction varies between approximately 20% for Chihuahua and almost 100% for Queretaro. The risk reduction in the RCP8.5 scenario varies between approximately 15% in Chihuahua and approximately 95% in Mexico. Note that these percentages are strictly a reduction in EAD; a flood that overtops the protection standard causes full damage.

(ii) Optimal protection standards for coastal floods

The economically optimal protection standards for coastal floods are significantly higher than those for river floods. Figure 4 shows that under constant climate conditions, all states that require additional investments to uphold or increase the protection standard have an optimal protection standard of 100 years or higher. Two states have an optimal protection standard of 1000 years, Baja California Sur and Sonora. This is mainly due to the effective protection of small stretches of coast that protect a larger hinterland, meaning that risk is relatively high with respect to flood protection costs, which is exacerbated with higher return periods. The achieved relative risk reduction for these high protection standards is very high, namely above 90% for most states (see electronic supplementary material, figure E3). The results show that the optimal protection standards vary when either protection costs rise faster than the benefits, or vice versa. For instance, the optimal protection standard for Tabasco moves from 250 years under constant climate conditions, to 50 years under RCP2.6 conditions, and back to 250 years under SLR100 conditions. For Jalisco, Nayarit and Chiapas, no additional investments are needed to reach optimal protection standards under all climate scenarios.

(c) Cost of adaptation

(i) Cost of river flood protection

Figure 5 shows the total present value of the costs for implementing the economically optimal protection standard over a 100-year period. The present value of the costs includes both the

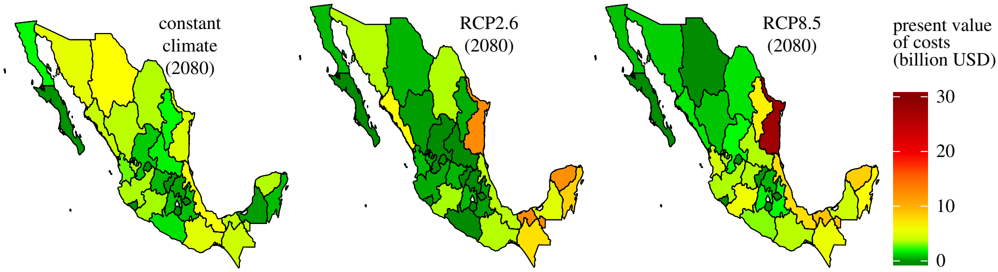

Figure 5. Present value of the total investment and maintenance costs of the optimal protection standards over a 100-year period for river floods for three future (2080) climate conditions and a discount rate of 10%.

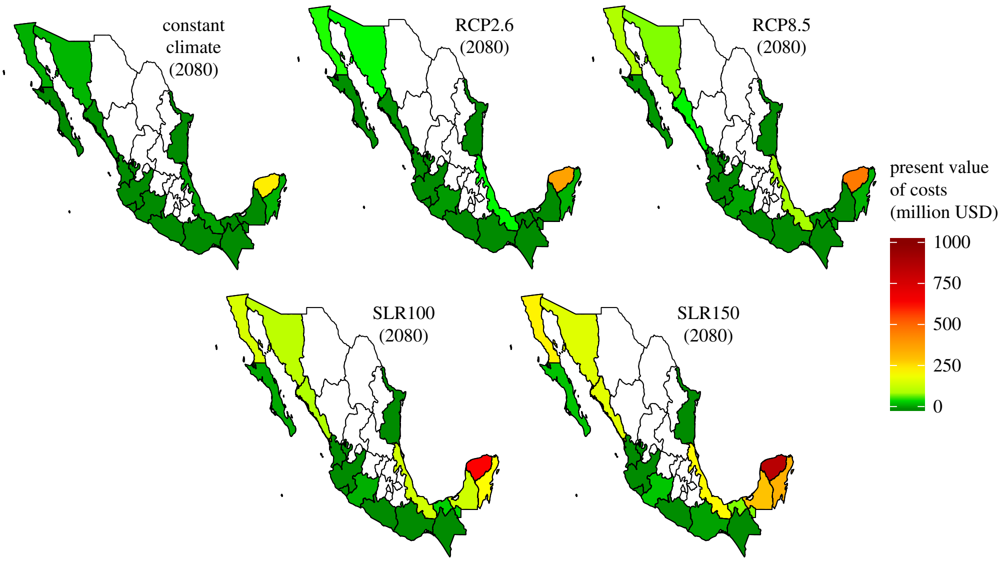

Figure 6. Present value of the total investment and maintenance costs of the optimal protection standards over a 100-year period for coastal floods for five future (2080) climate conditions and a discount rate of 10%.

needed investments and maintenance costs. For river protection, the costs for states that require additional investments to uphold or increase protection standards vary from 93 million USD for Queratero to 30 billion USD for Veracruz under constant climate conditions. Under the RCP2.6 scenario, several states would face costs below 1 billion to raise protection standards to optimal levels, such as Mexico, Queretaro and Zacatecas, but several other states such as Tamaulipas and Yucatan face costs over 1 billion USD to achieve optimum protection standards. Note that, although these are high costs, they do lead to the highest positive NPV, and are thus economically desirable. The results show similar findings for the RCP8.5 scenario, although fewer states need further investments to raise protection standards. Figure 5 shows clearly that most adaptation costs need to be made in the states along the Gulf of Mexico, which are home to the large river systems Rio Bravo, the Grijalva-Usumacinta, the Papaloapan and Coatzacoalcos. For a discount rate of 10%, the present value of the total costs in the whole of Mexico over a 100-year lifespan is 75 billion USD under constant climate conditions, which rises to 90 billion USD under the RCP2.6 scenario and 118 billion USD in RCP8.5.

(ii) Cost of coastal flood protection

The present value of the costs for coastal flood protection is much lower for most states than for river flood protection, even though the unit costs of coastal dykes are higher (figure 6). The reason is that the stretch of coast that needs protection is much shorter than the river dyke length needed, which is also reflected in the relatively low flood risk from coastal storm surges with respect to risk from river floods. The costs across states that require investment to increase protection standards against coastal floods under constant climate conditions varies between 3 million USD for Tabasco and 200 million USD for Yucatan. In general, the present value of maintenance and investment costs increases when sea level rises. Yucatan faces highest total costs under all climate scenarios, up to 600 million USD under the SLR150 scenario. Combined with Quintana Roo and Campeche, the Yucatan peninsula would face up to 1.5 billion USD under the SLR150 scenario. The total costs (present value) for Mexico would be 2.5 billion USD for the SLR150 scenario, while under constant climate conditions the total costs over the 100-year lifespan would be approximately 350 million USD.

(d) Model sensitivity

Considering the modelling uncertainties, we tested the sensitivity of the results to different assumptions on maximum damage values, indirect damage factors and discount rates. Electronic supplementary material C, tables C2–7, provide a detailed breakdown for each state how different parameter settings influence the results. Here, we discuss the summarized results for Mexico (electronic supplementary material C, tables C8 and 9).

For river floods the median optimum protection standard, including states that do not need investments, is 20–25 years under all settings except when decreasing the discount rate to 4%, which raises it to 50 years. The sensitivity of the optimum protection standard becomes larger under RCP2.6 and RCP8.5, ranging between 25 and 100 years, and 19 and 83 years respectively. Changing the discount rate has the most significant influence on the remaining risk after adaptation; a 4% discount rate leads to a 50–73% reduction of risk under different climate scenarios with respect to the baseline. Changing the maximum damage factor leads to a −17% to +17% change in remaining risk. Note that lower risk estimates can also increase the estimated risk after adaptation, as it might be more beneficial to set lower protection standards. Changing the indirect damage factor leads to a −14% to +17% change in remaining risk. When changing the maximum damage values or indirect damage factors, the cost of adaptation changes to −25% to +31% across settings and climate scenarios. Reducing the discount rate increases the cost of adaptation significantly, up to +228%, because high protection standards become more often economically efficient.

For coastal floods, the median optimal protection standard under the current climate is 21 years across parameter settings, as only a few states need additional investments. Under future scenarios, when changing the maximum damage or indirect damage factors, the median optimal protection standard varies between 100 and 500 years. Decreasing the discount rate to, for instance, 4% has the most profound effect, increasing optimal protection standards to 500 years under RCP2.6, and 1000 years under other climate scenarios. Setting different parameters for either the maximum damage values or the indirect damage factor reduces risk after adaptation between −45% (RCP8.5, indirect damage factor of 120%) to +51% (SLR100, indirect damage factor of 30%). Decreasing the discount rates to 6% or 4% leads to a reduction in remaining risk between 39% and 97%. The same as for river floods, lower initial risk estimates might lead to higher risk after adaptation, as the reduction in costs of lowering protection standard might outweigh the benefits of protection. The sensitivity of the remaining risk estimate results to the indirect damage factor and maximum damage is lower than to other parameters, ranging between −9% and +22%. Decreasing the discount rates leads to an increase of costs of 61% for the 6%, and 111% for the 4% discount rate.

5. Discussion and conclusion

The results presented here provide a first state-level coastal and river flood risk and adaptation assessment for Mexico. To the best of our knowledge, this is the first study that applies global datasets to a data-scarce country to assess both river and coastal flood risk in urban and non-urban areas, and analyses the costs and benefits of adaptation at the (sub-)national scale. The methods used are transferable to other countries or regions. By estimating both current and future risk, and by determining economically optimal adaptation strategies, the results provide first insights for policy makers to prioritize adaptation in different Mexican states. However, the results also show how limitations in the input data and uncertainties in parameter settings influence the risk estimates and estimates for economically optimal protection standards.

In general, we find that river flood risk is much higher than coastal flood risk. Our results show that especially several states along the Gulf of Mexico face high risk from river flooding, such as Tamaulipas, Yucatan, Tabasco and Veracruz. Consequently, they could benefit from additional funds to support flood protection, also under constant climate conditions. The Yucatan peninsula and Sonora and Baja California Sur face more risk from coastal flooding. Optimal protection standards for rivers for our baseline results are often close to a 20- to 25-year flood under constant climate conditions and under different parameter settings. River flood risk increases in most states, but it declines in a few where it is expected to become drier towards 2080. This implies that optimal flood protection standards increase in many areas, which imposes high adaptation costs, while in some states no additional flood risk adaptation investments are needed. Only a few states need additional investments for coastal surges under constant climate conditions. However, optimal standards for coastal flood protection under constant climate are higher, namely often 100 years or higher for different parameter settings under RCP2.6 and RCP8.5 conditions, and 250 years or higher under SLR100 and SLR150 conditions. A broader sensitivity analysis showed that decreasing the discount rate to 6% or 4% is found to have the largest influence on the results, by significantly increasing the number of states that need investments in river or coastal protection, increasing the median protection standards and reducing risk. Note that decreasing the discount rate is partly a political decision, where decreasing the discount rates places more value on future benefits of risk reduction.

Moreover, we show how assessing different future climate scenarios leads to significant differences in the development of risk, which has to be taken into account when steering adaptation policy. For the Mexican case study, if fossil fuels remain the world's dominant energy source (RCP8.5), central Mexico will become relatively wetter than if ambitious greenhouse gas reductions are reached globally (RCP2.6), which is especially relevant for river floods. Vice versa, this means that if the world does meet ambitious reductions in greenhouse gas emissions, the risk in the northwestern and southeastern states will be relatively higher. Coastal flood risk always increases for higher sea-level rise scenarios, which generally increases economically optimal flood protection standards. Also for the coastal states, different climate scenarios lead to different optimal protection standards. This has implications for policy makers, who have to determine an adaptation path that is most suitable in the political context of Mexico. For instance, they could adopt a precautionary approach, in which the highest protection standards among possible future climate scenarios are chosen. Or, a 'no-regret' strategy can be adopted, in which adaption is increased to meet the minimal optimal flood protection standard among climate scenarios, which can then be gradually updated when risk changes over time. The precautionary approach may be preferred by risk-averse policy makers, while the no-regret approach by policy makers who expect small and gradual increases in flood risk as a result of climate change.

In this study, we also show how assessing adaptation costs can guide governments in prioritizing fund allocation on a state level. Our assessment of adaptation costs for Mexico shows that meeting economically optimal safety standards will be substantial, even when low scenarios of climate change are anticipated. As an illustration, total discounted investment and maintenance costs of optimal flood protection standards under the baseline scenario for rivers are 90 billion USD in the whole of Mexico under the RCP2.6 scenario and 118 billion USD in RCP8.5 over a period of 100 years. The difference of the national aggregated costs is small, but the costs are larger on a state level, as the northwestern and southeastern states are wetter under RCP2.6 than under RCP8.5 conditions, while the central states are wetter under RCP8.5 than under RCP2.6 conditions. The sensitivity of these values to changing maximum damage values or indirect damage is between −25% and +31%. The costs of implementing optimal protection standards against coastal floods for the baseline scenario are strictly increasing across states, rising from 350 million USD for constant climate conditions to approximately 2.5 billion USD for SLR150 conditions. Sensitivity of these results varies between −45% and +51% when keeping the discount rate at 10%. Decreasing the discount rate to, for instance, 4%, and thereby valuing the reduction in future flood risk higher, increases adaptation costs for the coast to 106% under constant climate, and to 52% under the high-end SLR150 scenario.

The methodology applied here also showcases the application of global models for state-level application, which is relevant because local data are often lacking, incomplete or inconsistent. Recent developments in improved algorithms and resolution have made these global models, such as GLOFRIS, GTSR and FLOPROS, suitable for sub-national scale flood risk assessments [7], especially when no other consistent data are available, as is the case for Mexico. For instance, the GTSR dataset performs similar to many regional hydrodynamic models [28], GLOFRIS has been applied and validated successfully on global, national and sub-level scale [22,23], and FLOPROS provides the first database for many countries for flood protection [38]. Especially in data-scarce regions, these models are valuable for steering national adaptation funds to or building disaster relief capacity in regions where they are most needed. Our results show for instance that the states along the Gulf of Mexico face greatest risk, especially from river floods, and would benefit most from increased adaptation, but also need the most funds for increasing protection standards.

Although applying these global datasets overcomes data scarcity, they do come with limitations, and further research is needed to reduce uncertainties. For instance, GLOFRIS can be improved to better capture overland flow and inundation from direct rainfall, GTSR requires a better statistical analysis of tropical cyclones and analysis of wave run-up, the vertical accuracy of the MERIT DEM could be further improved, and FLOPROS needs to be expanded to provide global coverage for coastal flood protection. Moreover, most large-scale analyses of coastal inundation still make use of a simple bathtub model, which neglects storm duration, wind direction, water depth and surface roughness [32,43,44]. Only recently has the use of hydrodynamic models been explored at large scales [30], but its computational costs remain relatively high. Here we apply an attenuation factor scaled with the percentage permanent water, which improves upon the bathtub approach and on recent analysis where a constant factor was used [31]. Also, while the hazard maps applied here are state-of-the-art, return periods are currently estimated for river flows and sea levels separately, and as such they do not represent flood extents of actual events or compound river and coastal flood risk. Ideally, these hazard maps would be based on inundation mapping of long time series of flood events, for example, by applying more advanced extreme value statistics to the river flows or sea levels that incorporate the spatial extent of events. This could then be used to generate many synthetic flood events and compute updated corresponding inundation maps, and return periods could then be based on inundation depths or actual losses. However, for large-scale risk assessments this would result in a huge increase in computational costs, while the EAD may not be very different [45].

Furthermore, while the models applied here are useful for a state-level analysis, local implementation measures need to be supported by detailed local models that entail, among other things, (a) local meteorological data, (b) detailed local river geomorphology, (c) high-resolution digital elevation models, (d) high-resolution exposure data [7] and (e) local estimates of indirect economic flood losses from computable general equilibrium model approaches for Mexico [46]. Local flood risk management should ideally be an integrated process where adaptation pathways [47–49] are considered and where increasing protection standards are combined with other flood management options, such as land management, floodplain zoning, beach realignment, beach nourishment, and nature-based solutions such as mangroves or wetland restoration or creating room for the river. Especially for those states where our analysis finds negative NPV for protection with dykes, other options could be economically viable, and ideally, any local planning is based on integrated management which takes into account the concerns of all relevant stakeholders.

Data accessibility. All data that support the figures are provided in the electronic supplementary material.

Authors' contributions. T.H. and W.J.W.B. conceived and coordinated the study. T.H., W.J.W.B., V.R. and H.C. designed the methodological framework. T.H., V.R., H.C. and P.J.W. carried out the modelling. D.M.E. designed the coastal inundation model and produced the coastal hazard maps. J.Z.H. contributed with local expert knowledge. All authors were involved in drafting the manuscript. All authors gave their final approval for publication.

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